PARTICULATE ORGANIC MATTER IN KANEOHE BAY, OAHU, HAWAII

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HONOLULU, HAWAII TECHNICAL REPORT NO. 22 DECEMBER 1970

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December 1970

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Technical Report Number 22

ABSTRACT

During the 3-month period from March through May 1970, a study of particulate organic matter was undertaken in Kaneohe Bay. The Bay was divided into two basins on the basis of circulation and topography and eight stations along the length of the Bay were sampled at 5-meter intervals. Particulate organic carbon concentrations varied temporally, ranging at the sewer outfall from a high of 686 µg/l to a low of 121 µg/l. Concentrations were constant with depth and decreased with increasing distance from the sewer outfall. Particulate nitrogen displayed the same trends as particulate organic carbon, ranging in concentration from 117 µg/l to 27 µg/l at the outfall.

Total organic carbon concentrations showed similar trends, decreasing from 1.6 to 0.7 mg C/l, except at Station 2. At Station 2, high surface productivity, probably caused by increased dissolved organic concentrations, resulted in a total organic carbon concentration of 2.6 mg/l.

A carbon budget was calculated for the southern basin. Circulation and primary production were determined to be important factors in the high organic carbon concentrations in the Bay; sewage discharge and runoff were secondary sources. Sewage discharge is indirectly an important source of Bay carbon as the effluent's high nutrient content results in high productivity.

The residence time for organic carbon in the southern basin was calculated to be 5 days.

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INTRODUCTION

Despite considerable recent interest in the dynamics of organic matter in seawater, very little research has been done on organic matter in Kaneohe Bay. Gordon (unpublished data) determined particulate carbon and nitrogen at a station just off the Hawaii Institute of Marine Biology on Coconut Island. Klim (1969) studied the changes of dissolved and particulate organic carbon across the large barrier reef enclosing the Bay (Fig. 1). Some information on non-living organic matter in the Bay was also obtained during a pollution study by Young, et al. (WRRC Technical Report, in press).

This project was undertaken to study the dynamics of particulate matter in Kaneohe Bay and to attempt to construct a carbon budget for the Bay. It was done in conjunction with a pollution study by Drs. J. Caperon and S. A. Cattell, both of the Hawaii Institute of Marine Biology. Eight stations were established (Fig. 1) and, during the 3-month period from March through May 1970, the water at each station was sampled at 5-meter intervals from the surface to the bottom. The eight stations were chosen to provide representative sampling of the entire Bay with the emphasis on the southern basin. The eight stations are described in Table 1.

On all cruises, the water was analyzed for particulate carbon and nitrogen. On later cruises, particulate carbonate,

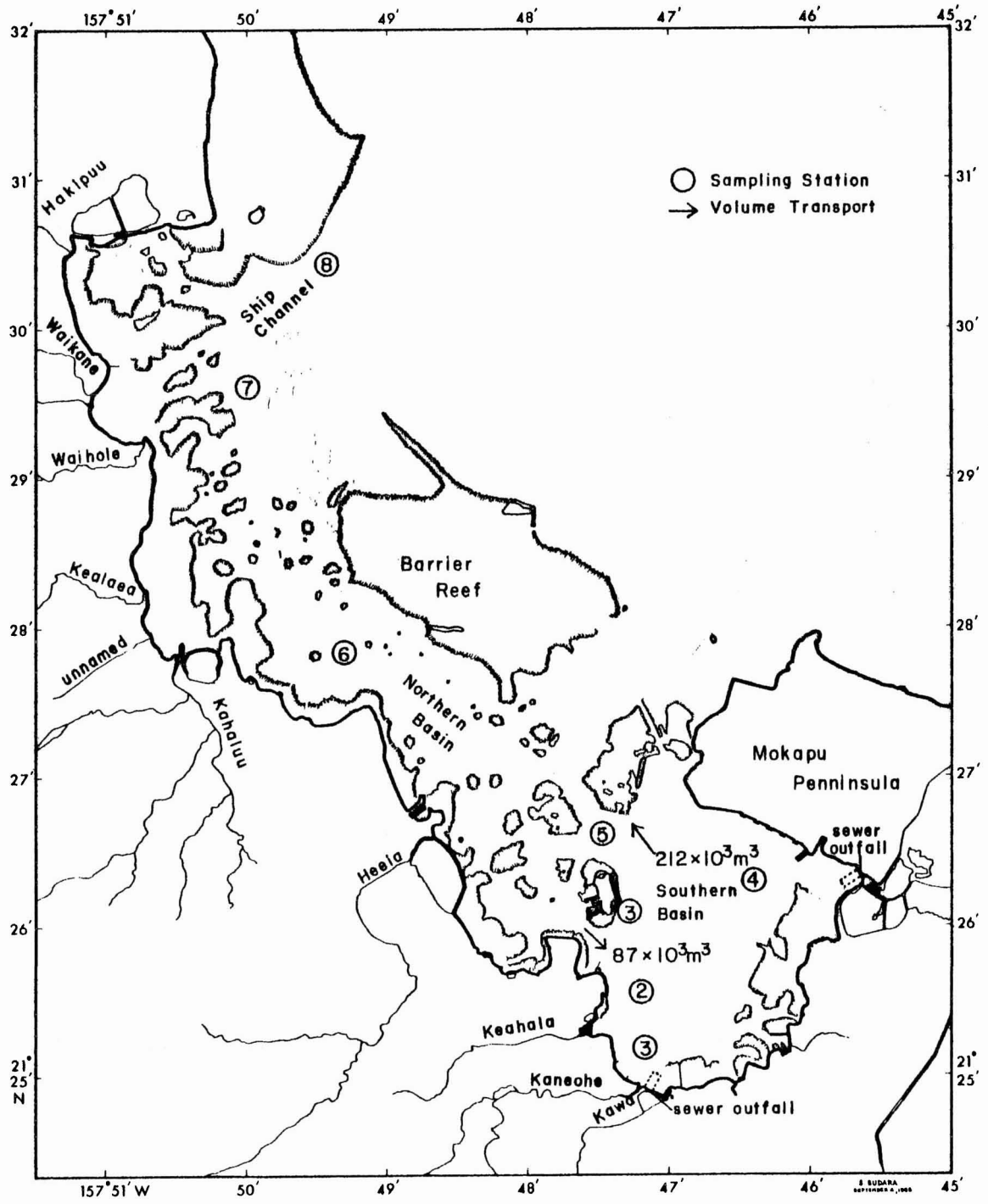

Figure 1. Chart showing configuration of Kaneohe Bay, station locations for weekly sampling cruises, streams feeding into the Bay, and volume transports for the two basins.

TABLE 1

STATION LOCATIONS FOR THE WEEKLY SAMPLING CRUISES IN KANEOHE BAY

Station	Location	Depth (m)
1	50 to 100 m off Coconut Island lagoon	13
2	At the white buoy at the Kaneohe Marina	8
3	Over a sewage plume from the Kaneohe Municipal Sewage Treatment Plant	5
4	On a line from the sewage plume to the middle hanger on Mokapu peninsula lining the northern end of Coconut Island up with the direction finder over Heeia Pond	13
5	At Buoy 27 off the northern shore of Coconut Island	13
6	At Buoy 17 inside the barrier reef	13
7	At Buoy 9 in the ship channel offshore of Waihole stream	13
8	At Buoy 3A in the main ship channel just past Chinaman's Hat	10

non-living particles, and total organic carbon were also analyzed.

For the carbon budget calculation, the sewage effluent from the military and municipal sewage treatment plans disposing of their effluent in Kaneohe Bay was analyzed for total organic carbon and particulate carbon and nitrogen. Sewage flow rates were obtained from the Division of Sewers, City and County of Honolulu and from the Sanitation Department of the Kaneohe Marine Corps Air Station.

The streams which flow into Kaneohe Bay (Fig. 1) were also analyzed for particulate and total organic carbon and particulate nitrogen. Fifty-year average flow rates were obtained from Gray and Lau (1970) and used for the budget calculations. These flow rates compared favorably with ones obtained from the Water Resources Division of the United States Geological Survey.

Productivity, chlorophyll a, and nutrient measurements were determined by others on the weekly cruises and some of the data will be mentioned herein.

Kaneohe Bay, situated on the northeast coast of Oahu, is an elongated embayment with its long axis running northwest-southeast (Fig. 1). It is about 7 nautical miles long and 2 nautical miles wide. Its depth ranges from 5 meters at the extreme southeastern end (Stations 2 and 3) to almost 15 meters in the dredged ship channel (Stations 4 - 8). An extensive barrier reef across the mouth of the Bay reduces free exchange of the water with the ocean (Fig. 1). Inside

the Bay, several small islands and many patch reefs restrict circulation further.

Bathen (1968) divided the Bay into three sections on the basis of circulation and topography. In this study, however, the Bay is divided into two sections: north and south (Fig. 1). The southern Bay is the southeast basin described by Bathen. It is approximately oval in shape, occupies 19.9% of the surface area, and contains 27.4% of the total volume of the Bay (Bathen, 1968). It is characterized by restricted circulation. The northern section is a composite of Bathen's middle and northern basins, and exhibits much freer exchange with the ocean.

METHODS

1. Sampling. On weekly cruises, samples were obtained by an in situ pumping system installed on the Hawaii Institute of Marine Biology's research vessel Salpa II. The water was drawn in through an intake, passed through about 4 meters of 2-cm-diameter garden hose connecting intake, pump, and fluorometer, and expelled through an exhaust covered with 300-μ plankton netting. The function of the netting was to remove the larger plankton. Sample depth was controlled by raising or lowering the intake. For surface samples, pump discharge was directed into a 6-l polypropylene container from which water was drawn. Deeper samples were collected directly from the discharge. In all cases, the water came in contact with only the teflon-

coated pump, hose, and fluorometer before being drawn for analysis.

The water for analysis was stored in 250-ml glass bottles for the half-hour between collection and filtration. The entire contents of each bottle was filtered on shipboard by gentle suction (1 to 2 psi) through 25-mm diameter, 1.2-μ pore-size Selas Flotronics silver filters on shipboard.

In an attempt to detect diurnal changes in the vertical distribution of particulate carbon, Station 1, near Coconut Island (Fig. 1), was sampled every 2 hours over the 24-hour period starting 0900 on 2 April 1970. Three days prior to this diurnal study, the station was sampled at 1-m intervals. The particulate carbon data from this earlier detailed profile were used to select the sampling depths for the diurnal study (surface, 3, 7, and 11 m).

During the diurnal experiment a smaller in situ pump (Scheisser, 1970) was used from a Boston Whaler. As on weekly cruises, the intake was lowered manually to the desired depth and the water, after passing through a 300-u mesh net, was collected directly from the discharge. The samples were collected, returned to the laboratory, filtered, and analyzed immediately. In the diurnal study only, 3.0-u silver filters were used and 1-l of water filtered. A comparison of the retention of the 1.2-μ and 3.0-μ pore size indicated that there was no significant difference in retention.

On Cruise 11 (19 May 1970), 250-ml aliquots were filtered through 25-mm-diameter, 1.2-μ pore-size Millipore filters on shipboard and returned to the laboratory for staining. On Cruise 12 (28 May 1970), total organic carbon was determined. The water was stored in 250-ml glass bottles which had been thoroughly pre-rinsed with sample water and returned to the laboratory for analysis.

On 1 May and 5 June, sewage effluent was collected from the Kaneohe Municipal Sewage Treatment Plant, and, on 22 and 27 May, effluent was obtained from the Kaneohe Marine Corps Air Station Plant. Samples were collected in 1-l bottles directly from the treatment plants prior to release into the Bay and returned to the laboratory for analysis.

The water in the streams that feed into Kaneohe Bay was analyzed twice (23 May and 5 June). Water was collected in 1-l bottles at sites just before the streams entered the Bay (Fig. 1), and returned to the laboratory for analysis.

2. Analytical. Particulate carbon and nitrogen concentrations were determined in an F & M Model 185 CHN Analyzer according to the methods of Gordon (1969). The filter was rolled, placed into the cavity in the injection rod along with a manganese dioxide catalyst, and injected into the combustion tube heated to 1080° C. The gaseous end products (CO_2, N_2, and H_2O) were swept by the helium carrier gas to a gas chromatograph. The chromatograph, connected to a recording instrument, measured the quantity of the gas by

peak height. Prior calibration with cyclohexanone-2,4 - dinitrophenylhydrazone allows one to convert peak height to carbon, nitrogen, and hydrogen concentrations. Hydrogen data were not worked up because this information was not needed. Therefore, the necessary precautions to insure accurate hydrogen determination were not taken.

Particulate carbonate-carbon was determined on Cruises 10 to 12 by treating some duplicate samples with 1% HCl while others, from the same station, remained untreated. The difference, after analysis in the F & M Analyzer, between the treated and untreated samples was considered to be the amount of particulate carbonate-carbon dissolved by the acid. Subtraction of the mean particulate carbonate-carbon value from the total particulate carbon concentration at each station resulted in the particulate organic carbon concentration at the station.

Total organic carbon was determined on Cruise 12 by the Menzel and Vaccaro method (1964) as modified by Strickland and Parsons (1968).

The staining behavior of the particles in reaction to an acid-Schiff carbohydrate stain and a bromophenol blue-acid protein stain was determined on Cruise 11 using the methods of Gordon (1970a). The Millipore filter was stained, dried in an oven, placed on a slide, and cleared with Permount.

The carbohydrate-stained samples were used to determine particle concentrations. Slides were examined at 200 X

magnification with phase contrast. In 1% of the filter area, or 50 fields all particles with a greatest dimension of 5 μ or larger were counted, and the total number of particles in each sample was calculated. In addition, relative particle size and type were noted.

RESULTS

1. Distribution of properties within the Bay.

A. Particulate organic carbon. The particulate organic carbon results of the nine cruises are summarized in Figure 2. A constant trend of decreasing concentrations as one moves up the Bay away from the municipal sewer outfall, as well as the similar decrease of the standard deviation, demonstrates that there is a steady trend towards lower particulate organic carbon values moving north. The only exception to this trend is found at Station 8. The nutrient data obtained by Dr. Caperon and the chlorophyll *a* data obtained by Dr. Cattell indicate that Station 8, and possibly Station 7, represent a different Bay area. When particulate organic carbon values are plotted on a semi-logarithmic graph, there is a logarithmic decrease as one proceeds up the bay to Station 5. After Station 5, this decrease is no longer observed.

There are no significant variations with depth at any of the stations.

Obvious temporal variations of particulate organic carbon were found only at Stations 2 and 3 (Fig. 3). Except on 7 April and 28 May, there is a direct correlation between the changes at Station 2 and 3. This indicates that the variations are related.

The mean of all of the eight stations on each sampling date is compared with the means of Stations 2 and 3 and with the means of Stations 1 and 4 to 8 (Fig. 4). The correlation of the first two means indicates that variations in particulate organic carbon concentration in the Bay are probably associated with the waste disposal in the sector particularly at the sewer outfall station (Station 3) and dominated by this and the corresponding changes at Station 2. There is little temporal variation in the particulate organic carbon concentration at the other stations.

The living plant carbon in the Bay can be estimated by applying a chlorophyll a-carbon correction factor to the particulate organic carbon concentrations in the Bay (Parsons, Stephens, and Strickland, 1961). From the widely ranging carbon-chlorophyll a relationship listed in the literature (Parsons, et al., 1961; McAllister, et al., 1961; and Steele and Baird, 1965), a mean value of 48.5 was obtained. By applying this value to the mean carbon and chlorophyll a values obtained in the Bay (Table 2), about 20 to 30% of the particulate organic carbon in the Bay is seen to be living plant carbon.

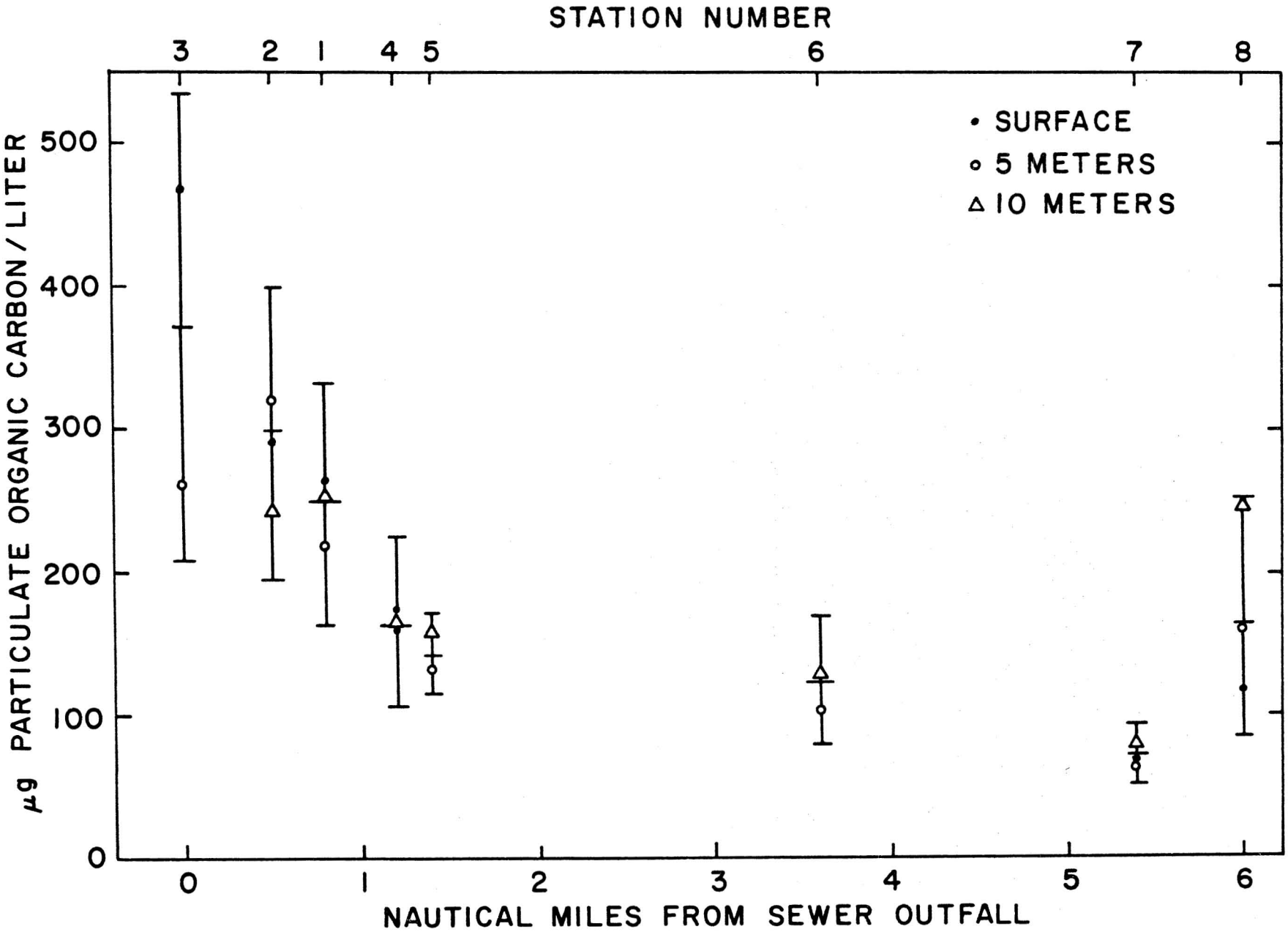

Figure 2. Mean Particulate organic cabon concentration and the standard deviation for each of the eight stations in Kaneohe Bay.

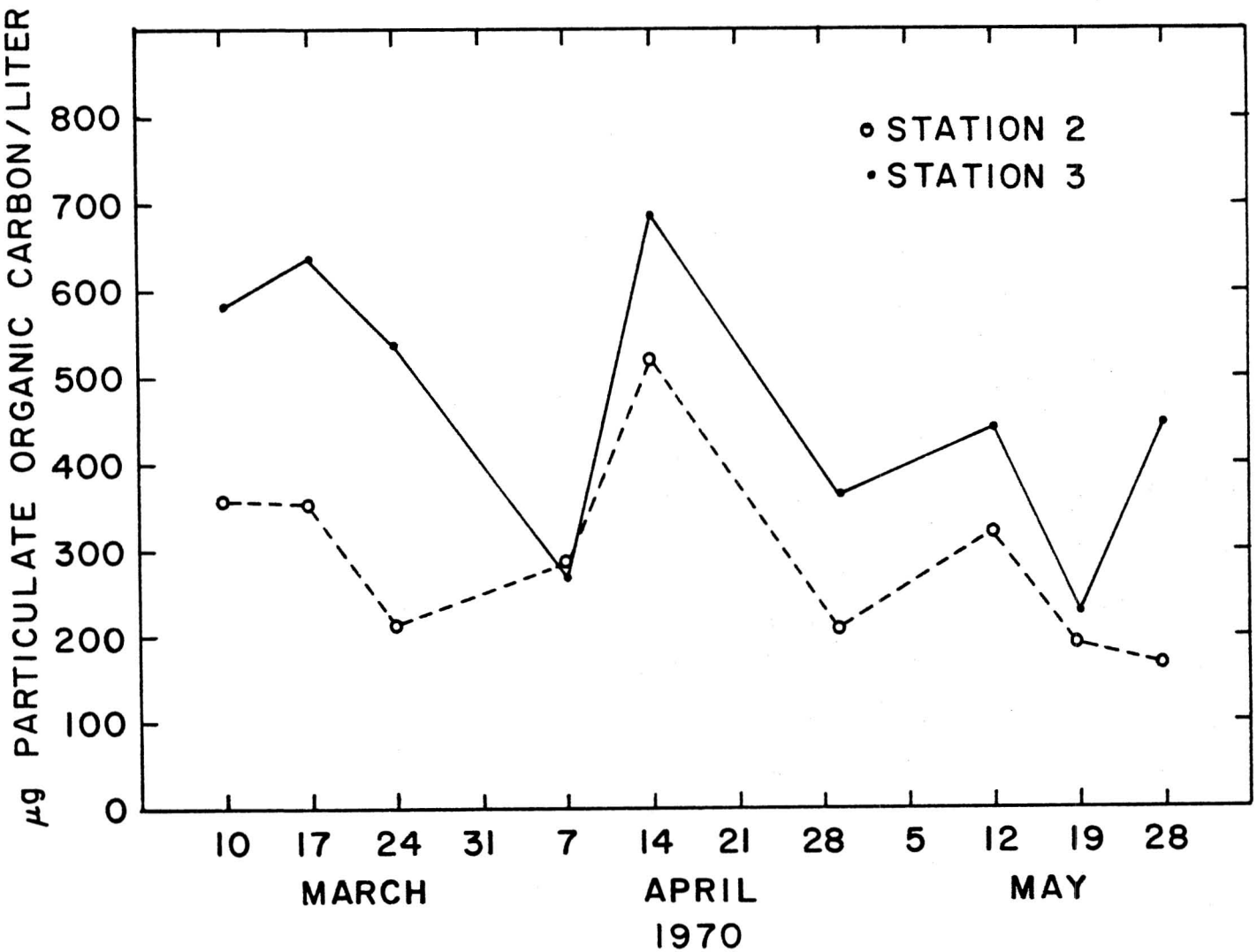

Figure 3. Comparison of surface particulate organic carbon concentrations at Stations 2 and 3.

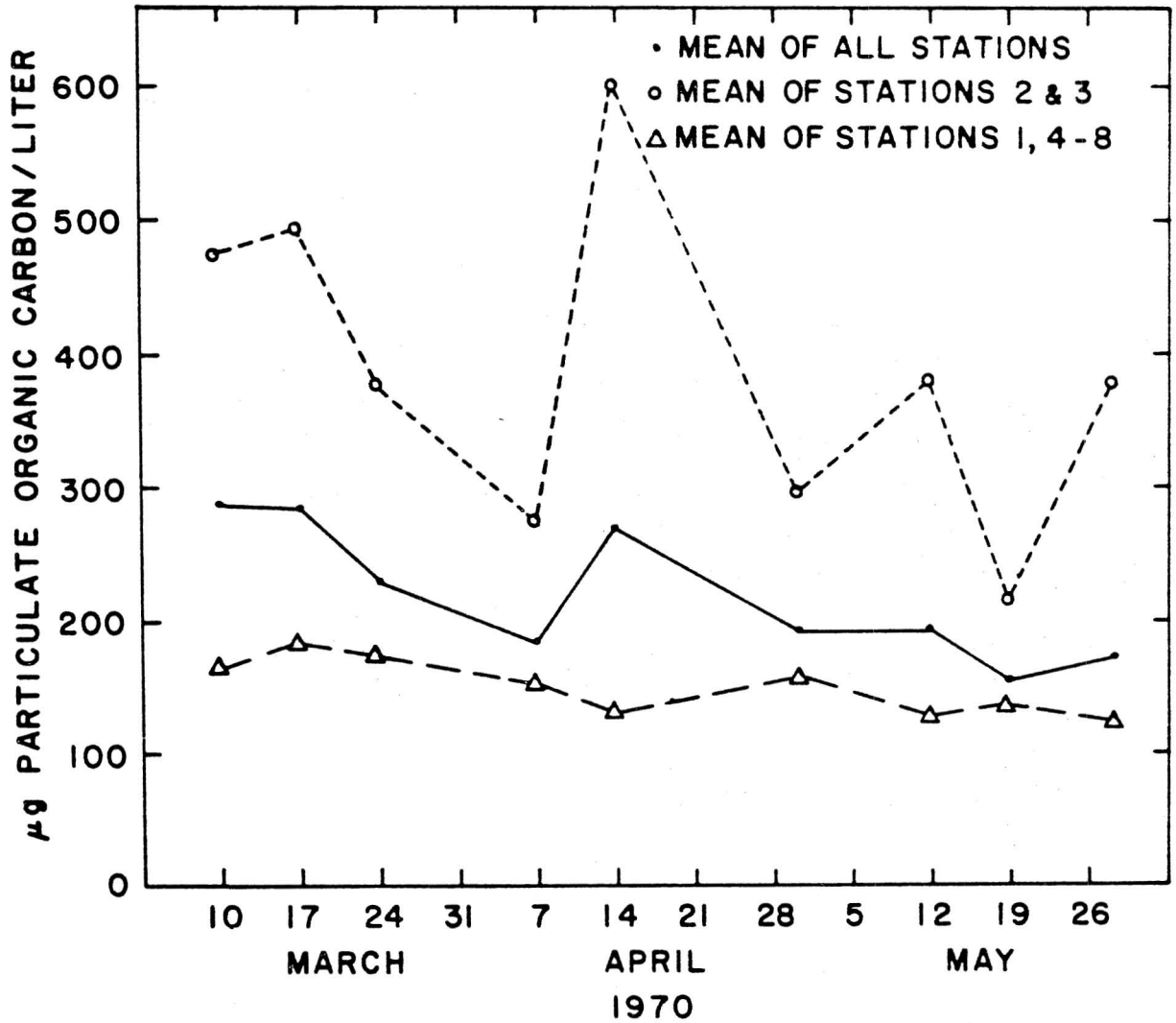

Figure 4. Temporal variations in the concentration of surface particulate organic carbon as shown by the mean of all stations, the mean of Stations 2 and 3, and the mean of Stations 1, and 4 to 8.

B. Particulate nitrogen. The mean particulate nitrogen values for all cruises at each station are plotted in Figure 5. As with the particulate organic carbon concentrations, one finds a steady logarithmic decrease away from the sewer outfall to Station 5. After Station 5, this decrease breaks down. In addition, the temporal changes at Stations 2 and 3 probably cause and certainly dominate over any variations at the other stations.

C. Carbon to nitrogen ratio. Concentrations of particulate organic carbon are plotted against those of particulate nitrogen in Figure 6. The scatter is due to points from Cruises 1 to 9 when particulate carbonate carbon was estimated; they contain more error. The carbon to nitrogen ratio for the particulate matter in the Bay is equivalent to the slope of the regression line which is 6.1. The remarkably constant carbon to nitrogen ratio obtained from the regression line suggests that relative concentrations of all components of the particulate organic matter in Kaneohe Bay remain constant with time, depth, and location.

D. Particulate carbonate-carbon. The absolute and percent mean particulate carbonate-carbon concentrations determined on Cruises 10 to 12 are presented in Figure 7. The percent carbonate-carbon is lowest at Station 3 because sewage effluent is primarily fresh water (Stone, personal communication). The logarithmic increase in percent

TABLE 2

CONVERSION OF PARTICULATE ORGANIC CARBON AND CHLOROPHYLL *a* TO LIVING CARBON USING THE PARTICULATE ORGANIC CARBON-CHLOROPHYLL *a* FACTOR OF 48.5

Substance mean value	Substance in mg/m^3 at each station							
	3	2	1	4	5	6	7	8
Chlorophyll a	1.88	1.28	.96	.69	.69	.29	.45	.41
Living plant carbon	91.19	62.08	46.56	33.46	33.46	14.06	21.82	19.88
Particulate organic carbon	375.0	229.1	293.1	128.0	120.0	111.4	62.5	72.9
Percent living plant carbon of the particulate organic carbon	24.3	27.0	15.8	26.1	27.8	12.6	34.9	27.2

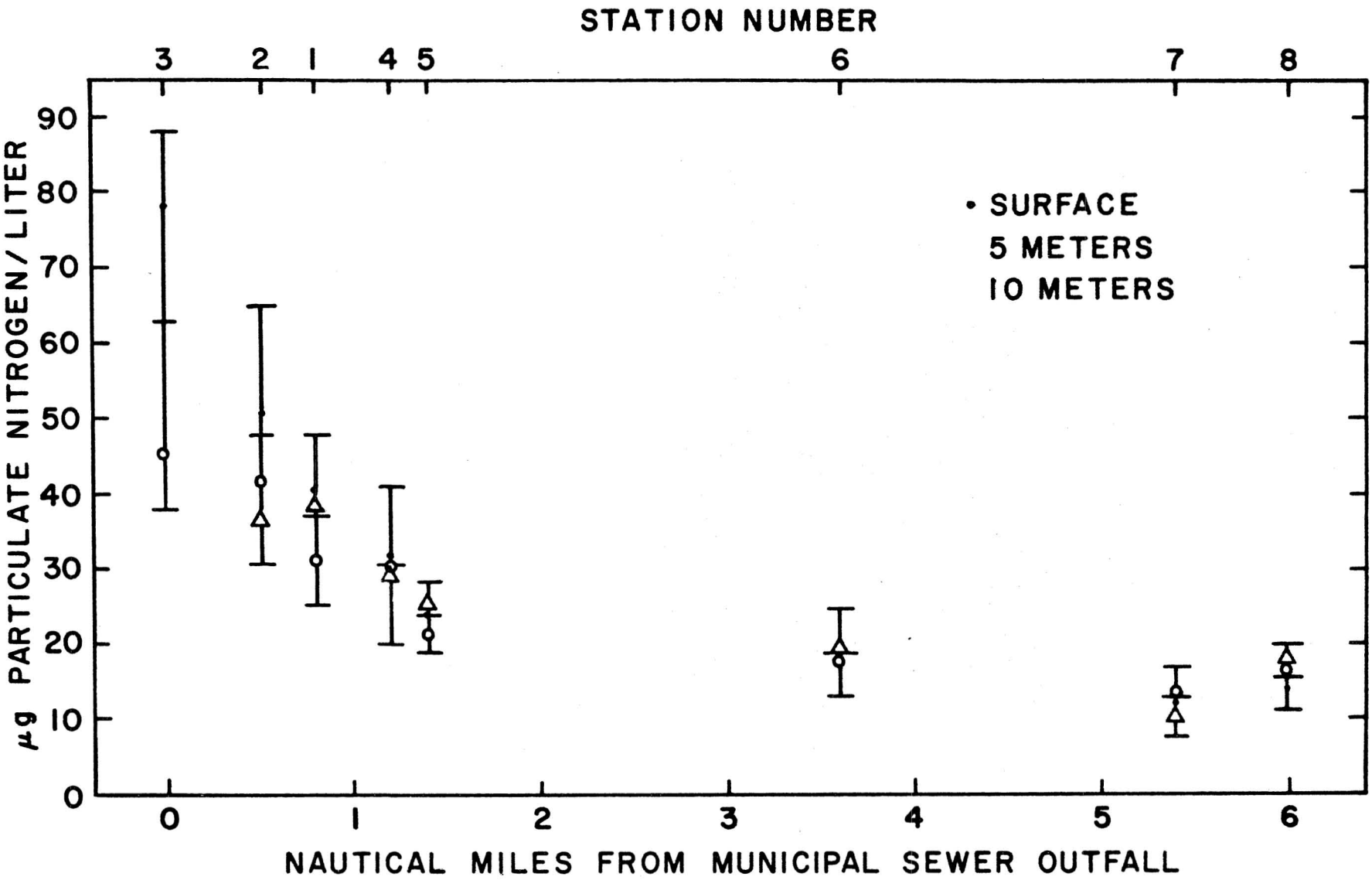

Figure 5. Mean concentration and standard deviation of particulate nitrogen at each of the eight stations in Kaneohe Bay.

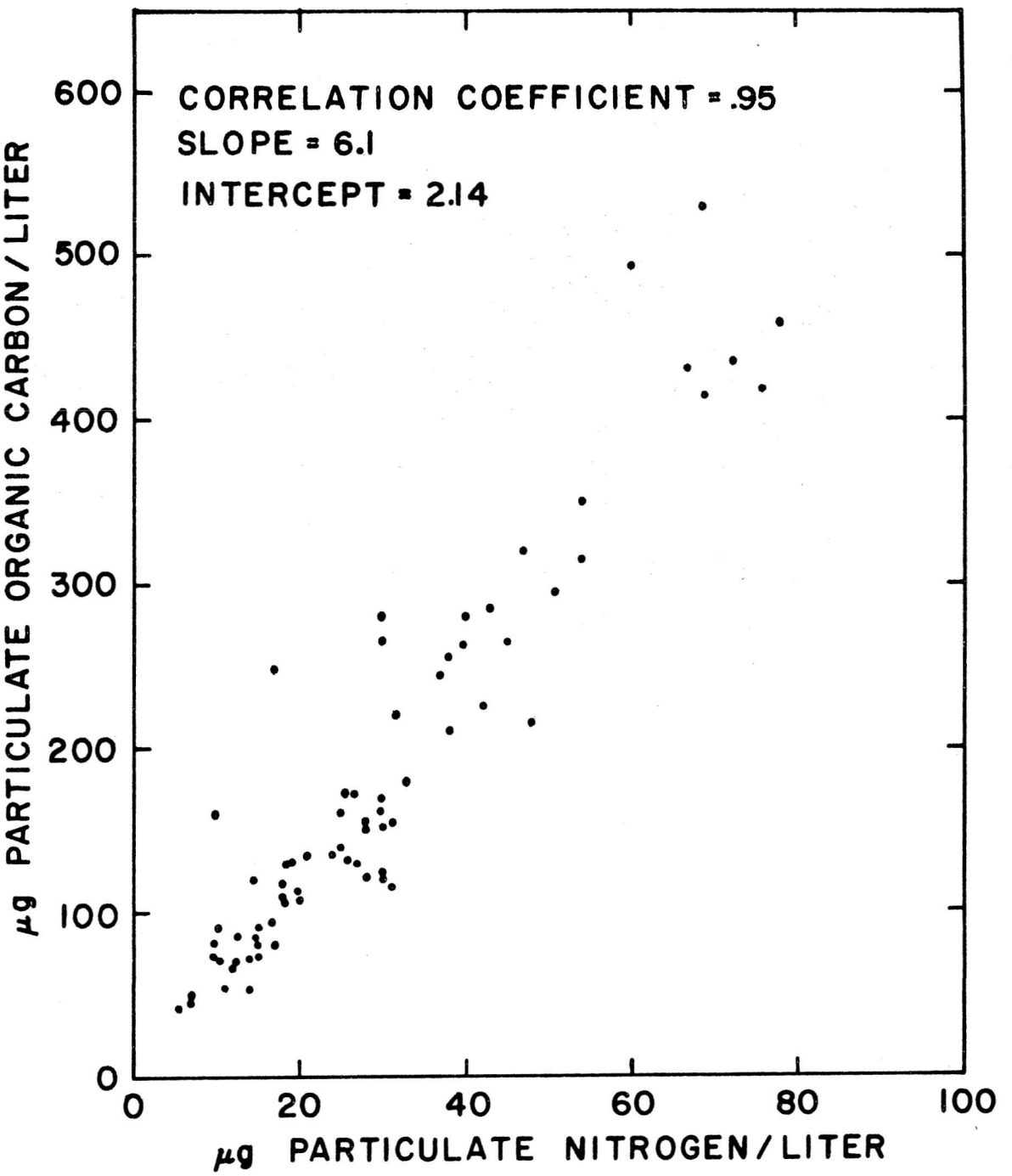

Figure 6. Relationship of particulate organic carbon and particulate nitrogen in Kaneohe Bay.

carbonate-carbon from the sewer outfall to Station 4 is a dilution effect. The low carbonate-carbon sewage effluent is diluted by the higher carbonate-carbon water in the Bay.

Stations 5 and 6 are near reefs. Klim (1969) indicated that carbonate-carbon is removed from the Bay water by the reefs. Therefore Stations 5 and 6 should have low particulate carbonate-carbon concentrations.

Bathen (personal communication) indicated that tidal currents across Chinaman's Hat reef stir up the sand and return it to the water column. Most of the sand in Kaneohe Bay is calcareous. Consequently, high particulate carbonate-carbon concentrations should be found at Stations 7 and 8 where the water contains sand.

E. Organic particles. Microscopic observation of the stained and mounted filters indicated that some particle trends exist in Kaneohe Bay. The general distribution of non-living organic particles larger than 5-μ is shown in Figure 8. There is a general decrease in the number of particles from Stations 3 to 7. This decrease is logarithmic. At Station 8 there is an increase in particle abundance at all depths. In general there was no significant change in particle concentration with depth.

The main types of particles observed are: (1) small flakes, thin, somewhat circular particles with a definite outline, heavily and evenly stained for carbohydrate resulting in a dark magenta color; (2) aggregates, larger particles with an indeterminate outline were usually stained

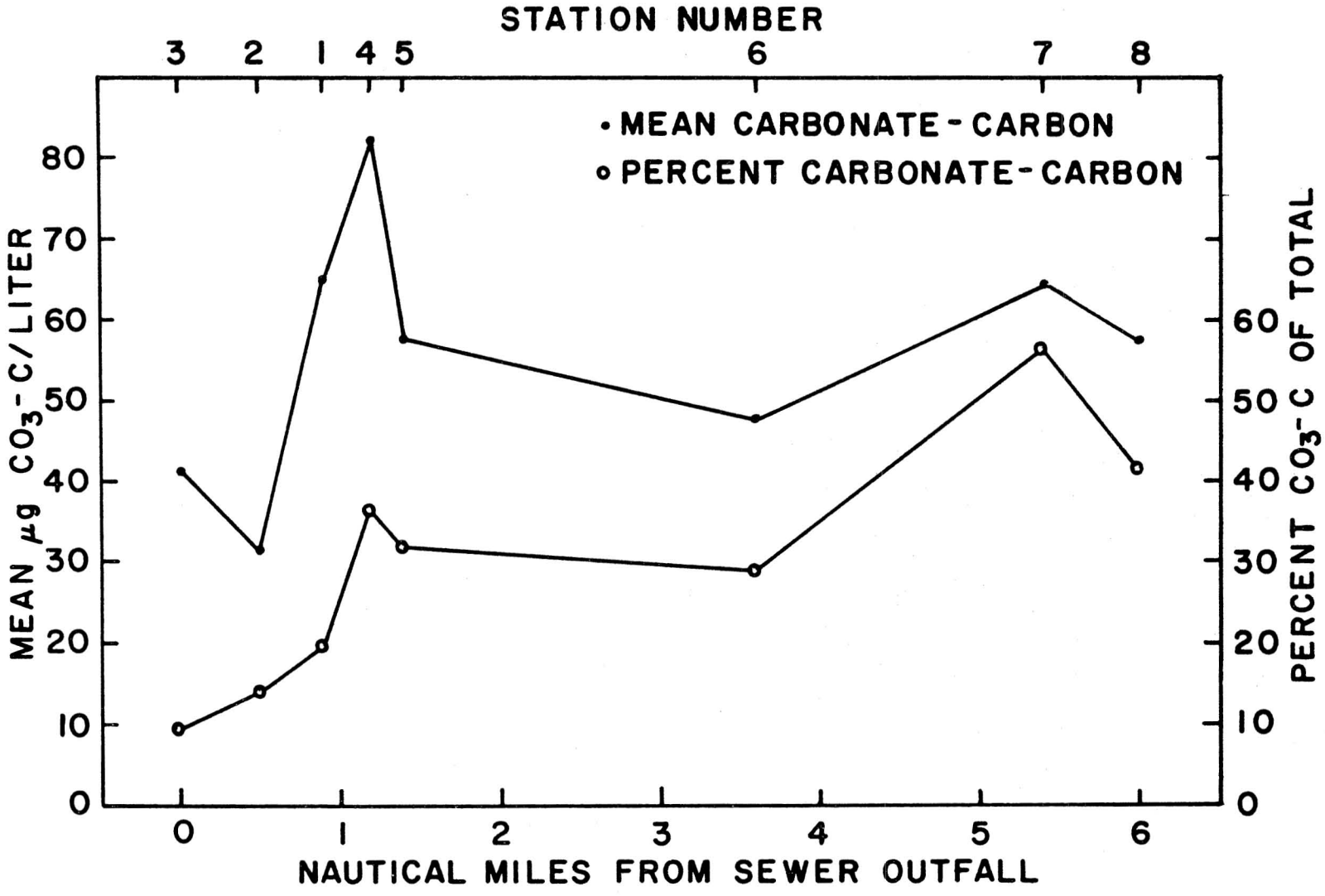

Figure 7. Mean carbonate-carbon and percent carbonate-carbon at eight stations in Kaneohe Bay.

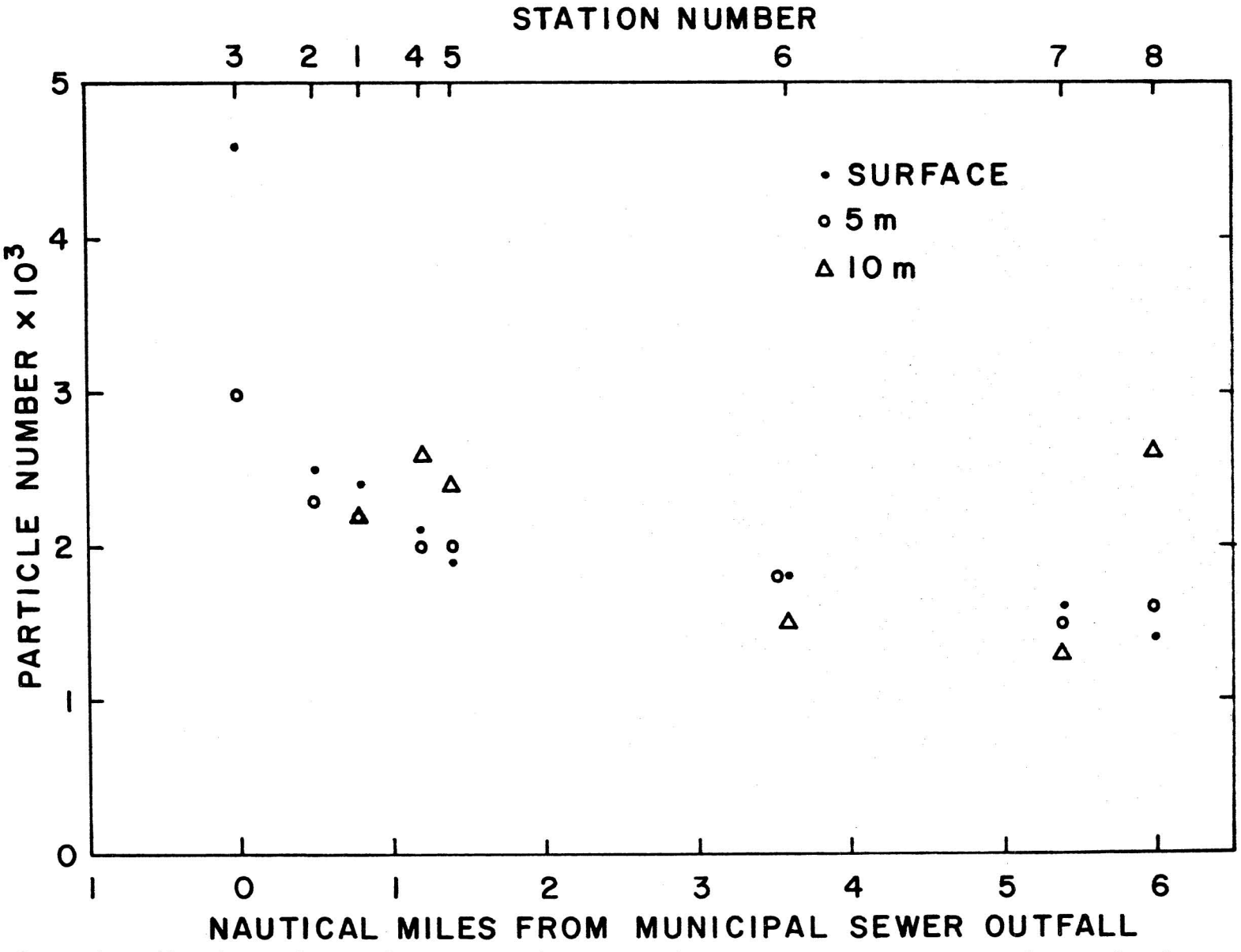

Figure 8. Distribution of particles at eight stations in Kaneohe Bay as determined on Cruise 11.

a light magenta or dark pink color and containing more darkly stained particles; and (3) clumps of flakes.

In general, moving from Station 3 to 7, there was a decrease in small flakes relative to an increase in clumps of flakes and aggregates. These were only relative changes, actually all types of particles decreased away from the municipal sewer outfall. At Station 8, particles increased in number and many small flakes similar to those which predominate in the southern basin were observed.

A good correlation between particulate organic carbon and non-living particle concentrations was found (Fig. 9). This indicates that counting is a fairly accurate method for determining particle concentrations.

F. Total organic carbon. The total organic carbon concentration at Station 2 is anomalous (Fig. 10). If Station 2 is omitted, some trends exist. Total organic carbon concentrations remain fairly constant with depth and decrease from 1.6 to 0.7 mg C/l up the Bay. This range is comparable to that found at Station Gollum by Gordon (1970b). The dissolved to particulate organic carbon ratio is 4.3, indicating an extremely high concentration of particulate organic carbon relative to dissolved organic carbon in the Bay water. At Station 2, these trends do not hold. The surface concentration of total organic carbon is 2.6 mg/l; at 5 m it is only 1.1 mg/l. Consequently, at Station 2, a definite vertical trend exists.

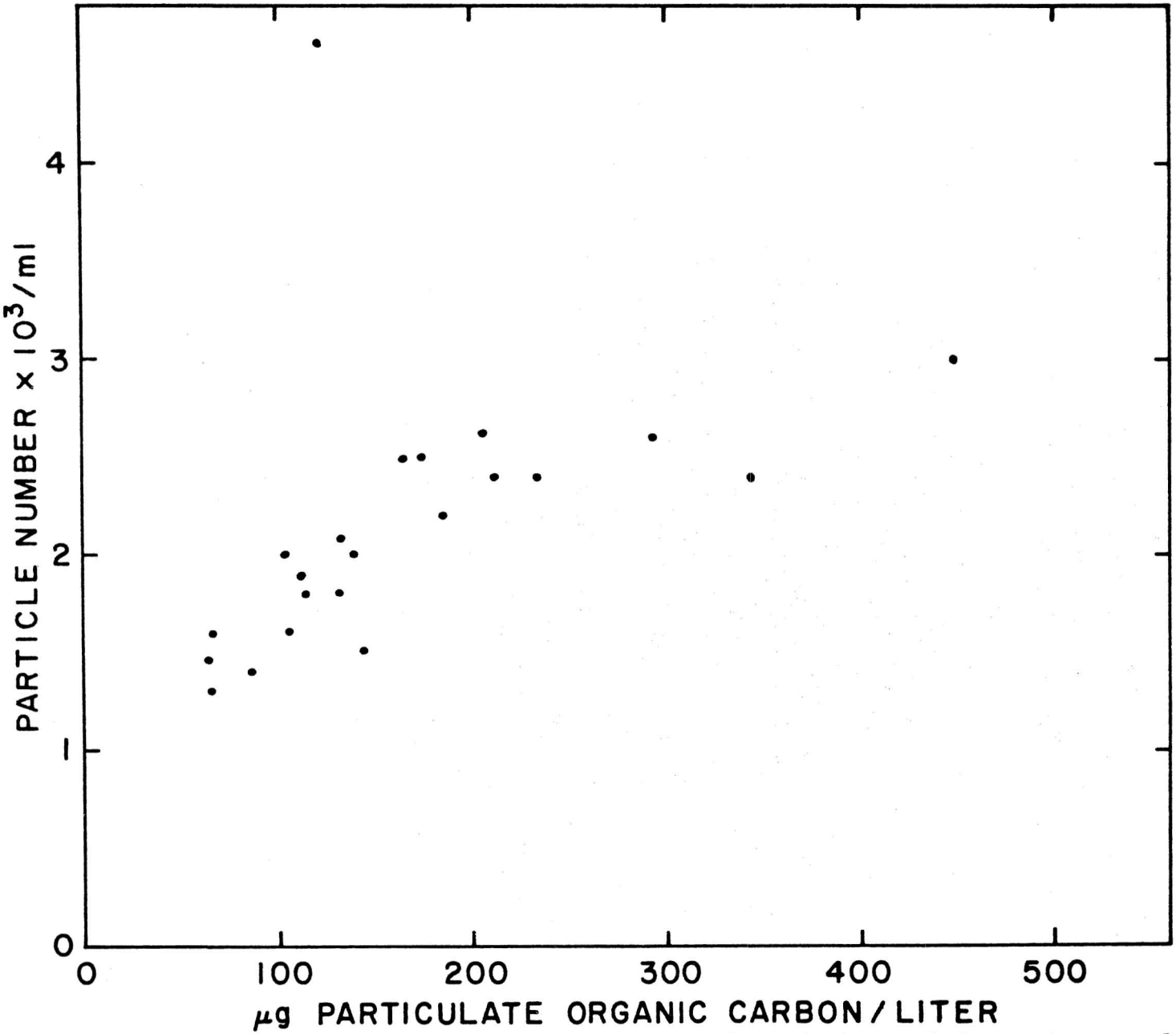

Figure 9. Plot of particulate organic carbon concentrations and particle number as determined on Cruise 11 for the eight stations in Kaneohe Bay.

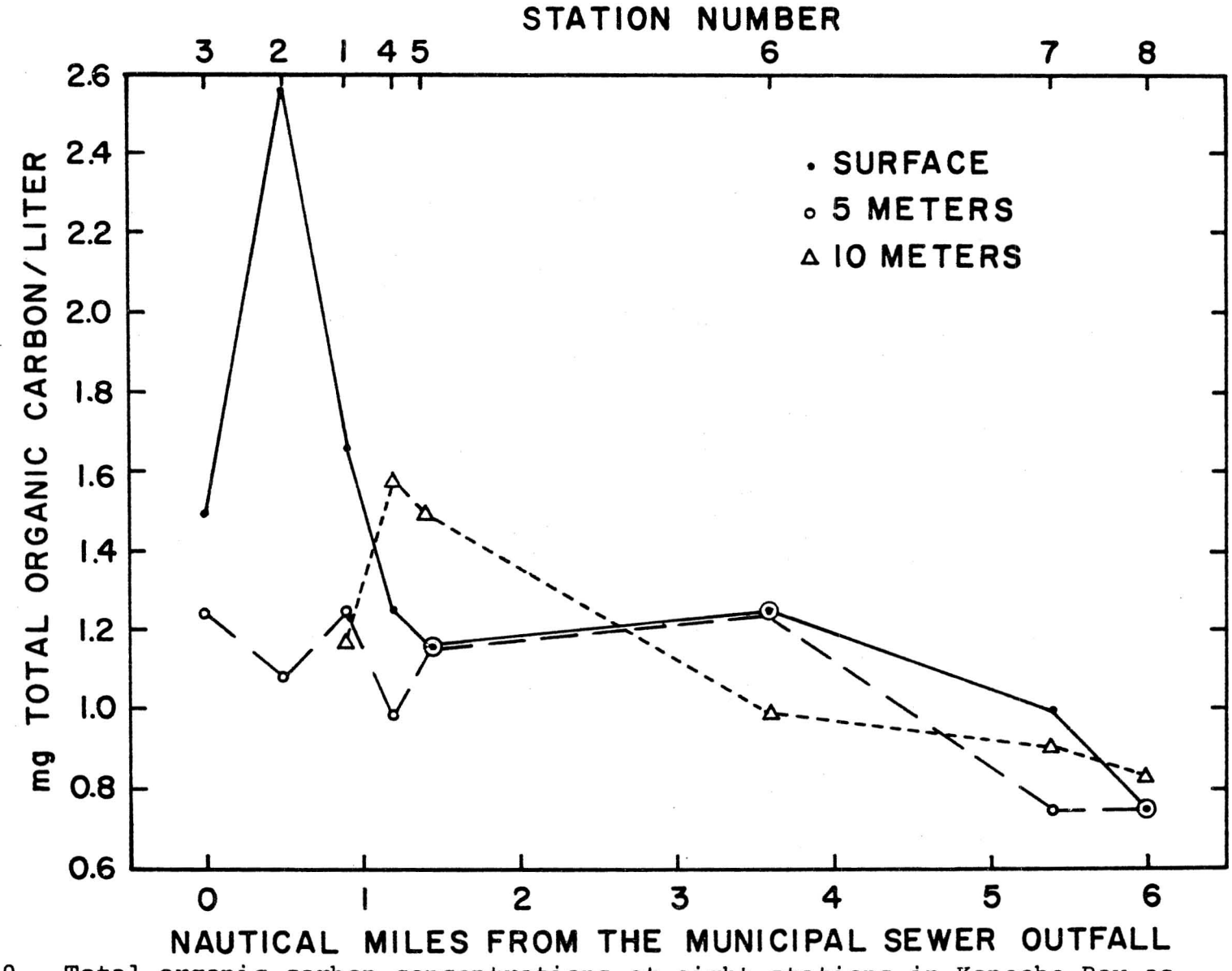

Figure 10. Total organic carbon concentrations at eight stations in Kaneohe Bay as determined on Cruise 12.

2. Diurnal station. The results of the diurnal study are summarized in Figure 11. Various tests were performed in an attempt to determine if diurnal variations occurred, but none were found. Instead it seems that the study measured the range in distribution of particulate organic carbon and nitrogen concentrations in the water column. The effect of this distribution is that repetitive sampling of one location yields varying results. It seems that 1-l volumes are not large enough to insure consistent results. Therefore, all samples collected on the cruises are likely to be biased by the volumes used. Consequently, the most accurate method for determining particulate carbon concentrations in Kaneohe Bay is to take many samples and use the mean concentration in any calculations.

3. Sewage effluent. The total organic carbon contribution by sewage effluent from the municipal and military plants to the southern basin was obtained by sampling the effluents. The effluent from the Kaneohe Municipal Sewage Treatment Plant varied slightly, but contained a mean concentration of 5.19 mg of particulate and 11.78 mg of total organic carbon/l, while the Kaneohe Marine Corps Air Station Sewage Treatment Plant effluent contained a mean of 10.82 mg of particulate and 21.78 mg of total organic carbon/l. To determine the amount of carbon added to the Bay by each plant, the flow records were obtained from the Division of Sewers, of the City and County of Honolulu, for the municipal plant and a mean flow was calculated. A mean flow rate

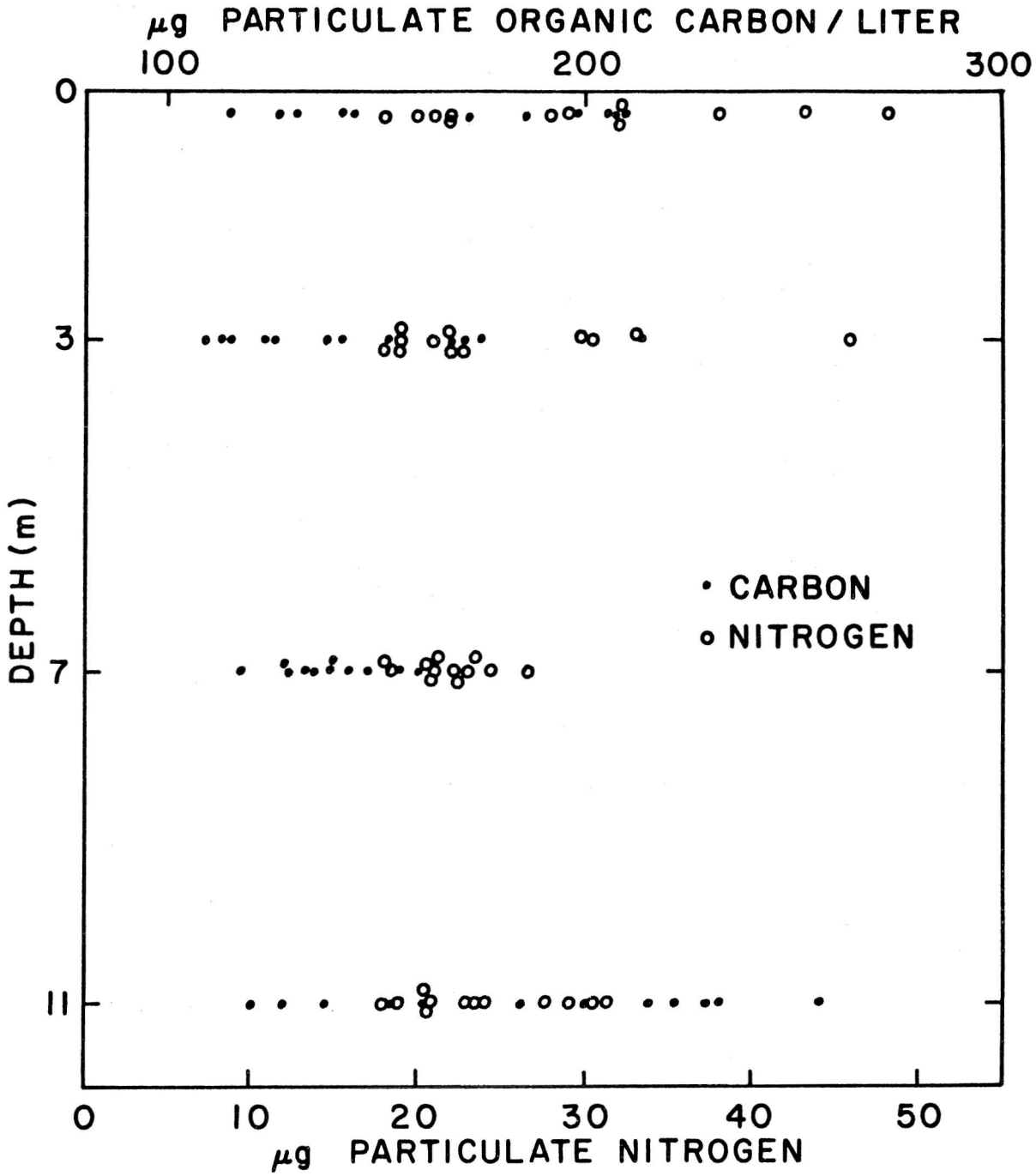

Figure 11. Range of particulate organic carbon and particulate nitrogen concentrations determined at four depths over the twenty-four hour period on 2 to 3 April 1970.

for the military plant was obtained from the Kaneohe Marine Corps Air Station, Department of Sanitation. Both plants add predominately fresh water to the Bay. The municipal plant adds a mean of 9.5×10^6 l of water/day and the military on 4.5×10^6 l/day. Using this information and the total organic carbon concentrations obtained from analysis of the effluents, it was determined that the military treatment plant adds 98.0 kg of total carbon to the Bay and the municipal plant adds 111.9 kg daily. Therefore, a total of 209.9 kg of carbon is daily added to Kaneohe Bay in the form of sewage effluent.

Microscopic examination of effluent revealed that the particulate component consists of many small particles (2 - 3 u).

4. Stream contribution. The carbon content of the streams varied from stream to stream and ranged from 871 ug to 3.278 mg of total organic carbon/l. These concentrations are comparable to those of Young, et al. (1970). Flow records were obtained from the Water Resources Division of the United States Geological Survey for several streams. The flow records were compared with the 50-year means listed by Gray and Lau (1970). Because the two were comparable, the 50-year mean was used as the more comprehensive rate. In this manner, it was determined that the streams add 343.4 kg of total organic carbon to the northern basin and 92.9 kg of total organic carbon to the southern one daily.

Therefore, a total of 436.3 kg of carbon is added to the Bay daily by the streams.

DISCUSSION

1. Distribution of properties within the Bay. Two factors are responsible for the high particulate organic matter in the southern basin: the restricted circulation and the sewage-discharge-stimulated productivity. Non-living organic particles, dissolved organic compounds, and mineral nutrients are added to the Bay by the effluents from the sewage treatment plants and they have relatively long residence times due to the restricted circulation. The high particulate organic carbon concentrations at the outfall appear to be due to an abundance of small non-living particles. These particles are diluted as the effluent mixes with the rest of the Bay. The utilization of the mineral nutrients by the phytoplankton and the organic nutrients by the heterotrophs results in living particulate organic carbon.

The productivity is rather different between Stations 2 and 3 although the amount of living plant carbon is almost the same. There are five factors that may account for this difference in productivity: (1) a lag between the uptake of the nutrients and the highest productivity would result in high productivity at Station 2, (2) inhibition of productivity in Station 3 phytoplankton by treatment chemicals

in the sewage effluent, (3) inhibition of productivity in Station 3 phytoplankton by an excess of nutrients, (4) inhibition of productivity at Station 3 by the fresh water in the sewage plume, and (5) preferential grazing on Station 2 phytoplankton producing a lower standing stock with a higher productivity. At this time it is not possible to assess the relative importance of these factors since they are outside the scope of this study.

Temporal variations in particulate organic carbon and particulate nitrogen are found at Stations 2 and 3 (Fig. 4). The variations may be caused by either sampling variability or zooplankton grazing. The diurnal study (Fig. 11) indicated that spatial variation in particulate organic matter does occur. The sampling frequency of the weekly cruises was insufficient to distinguish between spatial and temporal variation. Clutter (1970) indicated that zooplankton composition varied temporally. Any temporal variation in grazing pressure should result in temporal variations in particulate organic matter concentrations.

The logarithmic decrease in particulate and dissolved organic carbon, particulate nitrogen, and particle concentrations with increasing distance from the municipal sewer outfall in the southern Bay is probably due to dilution by mixing. If dilution is the only, or major, cause of the decrease, the increased circulation and tidal exchange in the northern Bay should destroy the logarithmic decrease.

This breakdown of the trend does occur.

Station 6 (Fig. 1) demonstrates the effect of the large reef on the Bay water. At Station 6, the water has the lowest percentage of living plant carbon (Table 2) and the lowest nutrient content (Caperon, unpublished data) in the Bay. Because the reef is a nutrient-dependent object, the water around it is nutrient depleted. Nutrient-depleted water should have a lower productivity and a lower percentage of living plant particulate organic carbon. Some of the dissolved and particulate organic carbon in the water is mucous material (Johannes, 1967) or other material washed off the reef. This would explain the slight increase in the total organic carbon concentrations in the lee of the reef (Fig. 10). Klim (1969) also observed that there is an increased concentration of dissolved organic carbon behind the reef.

At Station 7 the general decrease in concentration of particulate and dissolved organic carbon (Figs. 2 and 10), particulate nitrogen (Fig. 5), and non-living particles (Fig. 8) continues, while the percentage of living plant carbon (Table 2) and nutrients (Caperon, unpublished data) starts to increase. The increase in tidal exchange at Stations 7 and 8 seems to result in an increase in living material and nutrients. Bathen (personal communication) reports that during tidal flushing of the Bay, the sediment on Chinaman's Hat reef is stirred up. This roiling of the

sediment into the water would also return the temporarily unavailable nutrients to the water column. An increase in living plant carbon should result.

Station 8 is obviously different from all the other stations in the Bay. It is outside Bathen's (1968) division for the inner Bay, and has anomalously higher concentrations of particulate organic carbon (Fig. 2), particulate nitrogen (Fig. 5), nutrients (Caperon, unpublished data), non-living particles (Fig. 8), and living plant carbon (Table 2). Neither is it an oceanic station. The open ocean has much lower concentrations of all properties than observed at Station 8. Bathen indicated (personal communication) that there is a slight current running along the windward face of the barrier reef. This current could carry southern basin water, after some dilution by mixing, to Station 8. Such a water transport would explain many of the anomalous properties of Station 8.

The constant carbon-to-nitrogen ratio indicates a fairly constant composition of particulate organic matter in the Bay. Various references differ on the value for living material, but it lies within the range of 4.4 to 15, averaging about 8 (McAllister, et al., 1961; Parsons, et al., 1961; Menzel and Ryther, 1964; and Holm-Hansen, 1969). Somewhat lower values were found in the Bay. This could be due to the sewage effluent which has a carbon-to-nitrogen ratio of 6.0.

The carbon-to-nitrogen regression (Fig. 6) approaches zero. This important observation indicates that there is no preferential use of the particulate organic matter in the Bay.

Vertical variation in particulate organic matter concentration with depth does not generally show up. Krasnick (unpublished data) observed little change of productivity from full to 40% illumination. My diurnal study indicated that particulate organic matter is randomly distributed throughout the water column. It would seem that any variation in particulate organic matter with depth is introduced by sampling error rather than actual variation, and that vertical mixing is quite effective in dispersing particulate organic matter.

Bathen (1968) indicates that there is a slight vertical gradient in density layers in the Bay. This would tend to slow down vertical mixing in the Bay, and consequently, tend to slow down homogenization of the particulate organic matter concentrations. As a result, the lack of vertical variation in particulate organic carbon concentration with depth indicates that rates of change in concentrations of particulate organic matter are low relative to mixing rates.

Gordon (1970b) found that dissolved organic carbon and particulate organic carbon concentrations at Station Gollum, 20 miles off the north shore of Oahu, ranged from 1.1 to 3.1 mg/l and 12 to 30 ug/l, respectively. The range of

dissolved organic carbon concentrations found in Kaneohe Bay (1.3 to 0.7 mg/l) is similar to that found offshore, while the range of particulate organic carbon concentrations (370 to 72 ug/l) is much higher. The high productivity and sewage discharge probably cause the higher particulate organic carbon concentrations in the Bay, while particulate organic carbon formation and heterotroph utilization of dissolved organic carbon keep the dissolved organic carbon concentrations low. Gordon's values from the open ocean give a dissolved to particulate organic carbon concentration ratio of 100:1, while mine from the Bay result in a 4 to 5:1 ratio. This further illustrates the relatively high particulate organic carbon concentrations found in Kaneohe Bay.

2. Carbon budgets.

A. Southern basin. The principal reasons for the organic carbon enrichment of the southern basin are: (1) high productivity, (2) restricted circulation, (3) sewage discharge, and (4) stream runoff. In an attempt to show the relative importance of each of these factors, a carbon budget (Table 3) for the southern basin is calculated. Sources of input (primary productivity, circulation, sewage discharge, and stream runoff) are balanced against output losses (respiration, circulation, and settling).

Krasnick (personal communication) determined particulate carbon fixed/m^3/hour at the eight stations on the weekly cruises. Taking a mean value for the four stations in the

southern basin (23.87 mg/m^3/hour), correcting it for 12 hours of sunlight, it is calculated that 286.4 mg of total organic carbon are fixed/m^3/day. Because the volume of the southern basin is 70.8 x 10^6 m^3 (Bathen, 1968), 20,277.1 kg of carbon are fixed daily in the southern basin.

The circulation in the southern basin is an exchange of water with the northern basin. According to Bathen (1968), 87 x 10^3 m^3/day enter the basin southwest of Coconut Island and 212.2 x 10^3 m^3/day leave it northeast of the island (Fig. 1). Using the mean total organic carbon concentration for each basin as the carbon concentration in the water exchanged, and Bathen's volume transports, it is calculated that 89.1 kg enter and 303.0 kg leave the southern basin daily.

Sewage effluent and stream runoff play a minor part in the carbon budget by adding 209.9 and 92.9 kg of total organic carbon to the Bay, respectively (Table 3).

The daily loss of carbon to respiration must be estimated. The literature contains many studies of respiration over coral reefs (Odum and Odum, 1955; Odum, 1956; Kohn and Helfrich, 1957; and Gordon and Kelly, 1962). Although many parts of Kaneohe Bay have coral reefs, the major portion of the Bay does not. Therefore, the respiration rates given in the literature are too high for Kaneohe Bay. Gordon (1970c) obtained a respiration rate for Fanning Island lagoon of 151 mg/m^3/day. Fanning

Island, located in the equatorial region of the North Pacific Ocean, is similar to Kaneohe Bay both in carbon concentration and in productivity. Gordon's respiration rate will be used for the carbon budget. Because there are 70.8×10^6 m^3 of water in the southern basin (Bathen, 1968), the respiration loss of organic carbon is 10,609.8 kg daily.

Chave and Scheisser (1970) determined that 9% of the dissolved organic carbon in Kaneohe Bay waters is lost to the sediments daily. The mean dissolved organic carbon concentration in the southern basin is 1.19 g/m^3, the volume 70.8×10^6 m^3, and the total weight of dissolved organic carbon is 84.2×10^3 kg. If 9% is removed, then 7,578 kg of carbon are lost to the sediments daily.

Table 3 summarizes the above figures and the values for input and output balance quite nicely with a discrepancy of only 2,101 kg. Two possible reasons for the discrepancy are: (1) the estimate for the carbon concentration lost from the basin by circulation is too low and (2) the respiration rate chosen is inaccurate. The first would have a negligible effect on the results, but the second would have a considerable effect. Odum (1956) noted that areas of pollution have higher respiration rates than unpolluted areas. Because the sewage effluent is discharged into the Bay, the areas around the outlets probably have higher respiration rates than the 151 mg/m^3/hour used. This would raise the respiration rate in the southern basin and,

consequently, balance the input. If the input is balanced with the output, a respiration of 182 mg/m^3/hour is obtained.

TABLE 3

CARBON BUDGET FOR THE SOUTHERN BASIN

Input (kg/day)		Output (kg/day)	
Sewage effluent	210	Circulation	303
Stream runoff	93	Respiration	10691
Circulation	89	Settling	7578
Photosynthesis	20277		
Input	20673	Output	18572

From the organic carbon budget, one can see that the organic carbon from the sewage effluent has little direct effect of the organic carbon budget in the Bay. Therefore, the organic carbon from the treatment plants does not appear to be an important energy source in the southern Bay community. However, the high nutrient concentrations of the sewage effluent does appear to have a pronounced indirect effect on the carbon budget. The nutrients stimulate phytoplankton growth which in turn results in high concentrations of particulate organic carbon. Thus the high carbon concentrations in the southern part of the Bay are a result of sewage discharge.

B. Northern basin. No carbon budget was calculated for the northern basin because the concentration of total organic carbon in the water entering the Bay was unknown and the volume transports listed in Bathen (1968) may contain considerable error (Stroup, unpublished report). However, particulate organic carbon fixed by primary productivity, dissolved organic carbon lost to the sediments, and total organic carbon contributed by stream runoff were calculated.

The runoff, or stream contribution, has already been calculated to be 343.4 kg of total organic carbon day.

A mean productivity for the northern basin was obtained from Krasnick's data (personal communication). From the basin's volume (187.3×10^6 m^3) and the daily mean productivity (92.02 mg/m^3), it was calculated that 17,118.5 kg of total organic carbon are fixed in the northern basin.

Carbon lost to the sediments was determined in the same manner as for the southern basin. A mean dissolved organic carbon concentration was obtained (0.82 mg/m^3) and converted to concentration of dissolved organic carbon for the whole basin (153.2×10^3 kg). The 9% loss to settling was calculated and found to equal 13,788 kg/day.

3. Residence Time. The residence time of organic carbon in the southern basin was estimated by dividing the amount present by the rate of either input or output. Using the input method, a 5-day residence time was calculated.

This compares favorably with the 4 to 7 day residence time calculated for the southern basin by Bathen (1968).

SUMMARY

1. Particulate organic carbon and nitrogen concentrations in Kaneohe Bay are uniform with depth and decrease rapidly with increasing distance from the municipal sewer outfall.

2. Living plant carbon represents only 20 to 30% of the total particulate organic matter.

3. A constant carbon-to-nitrogen ratio of 6.1 was found irrespective of time, depth, or location.

4. Particulate carbonate-carbon varies from station to station and ranges from 9 to 50% of the total particulate carbon.

5. Major factors for high carbon concentrations in the Bay are circulation and photosynthesis; secondary sources are runoff and sewage discharge. The sewage effluent's high nutrient content is an indirect source of high carbon as it stimulates productivity.

6. Carbon has a residence time of 5 days in the southern basin.

APPENDIX I

CONCENTRATION OF PARTICULATE ORGANIC CARBON AT EACH STATION

IN µg C/l

Cruise	Date 1970	Depth (m)	Station 3	2	1	4	5	6	7	8
1	10 March	0	538	359	287				101	108
2	17 March	0	638	350	164	236	178	137		
		5	292	407	261	270		159		278
		10			281	195		173		
3	24 March	0	549	215	259	235	163	165	53	184
		5	358	412		185	192	124	86	148
		10		222		196	155	124	127	174
5	7 April	0	267	287	230	139	142	227	51	141
		5	210	225	166	198	158	126	71	
		10			211	125	163	102	88	

APPENDIX I (CONTINUED)

CONCENTRATION OF PARTICULATE ORGANIC CARBON AT EACH STATION

IN µg C/l

Cruise	Date 1970	Depth (m)	Station 3	2	1	4	5	6	7	8
6	14 April	0	686	521	258		120	81	58	145
		5	362	403	98	134	123	100	78	
		10		270	170	149	123	77	79	236
8	30 April	0	367	212	296	170	125	104	94	157
		5	205	251	196	175	99			
		10			237		136			
10	12 May	0	443	321	424	82	109	69	53	48
		5	296	443	453	72	121	64	35	155
		10			344	62	192	162	51	159
11	19 May	0	234	193	219	172	136	147	68	84
		5	269	256	174	161	118	42	63	126
		10			203	254	139	120	76	377

APPENDIX I (CONTINUED)

CONCENTRATION OF PARTICULATE ORGANIC CARBON AT EACH STATION

IN µg C/l

Cruise	Date 1970	Depth (m)	Station 3	2	1	4	5	6	7	8
12	28 May	0	448	173	236	139	116	118	67	87
		5	121	165	186	104	139	131	65	196
		10			344	205	213	145	67	294
Mean for all depths and all cruises			372	299	248	166	144	123	72	167

APPENDIX 2

CONCENTRATIONS OF PARTICULATE NITROGEN AT EACH STATION IN µG

Cruise	Date 1970	Depth (m)	Station 3	2	1	4	5	6	7	8
1	10 March	0	96.0	64.4	46.4				19.2	14.2
2	17 March	0	96.7	63.0	23.2	36.7	28.0	18.9		
		5	41.2	51.6	45.6	50.2		20.6		22.5
		10			41.8	36.0		20.6		
3	24 March	0	75.5	35.6	35.6	42.0	27.4	25.4	10.0	19.0
		5	58.4	49.6		33.2	28.0	20.4	16.4	19.0
		10		28.0		39.6	26.8	21.6	20.4	22.2
5	7 April	0	48.4	51.2	34.0	40.8	23.6	27.6	8.6	15.6
		5	36.8	36.8	28.2	27.6	26.4	20.8	10.4	
		10			28.9	24.8	24.8	24.4	11.0	

APPENDIX 2 (CONTINUED)

CONCENTRATIONS OF PARTICULATE NITROGEN AT EACH STATION IN μG

Cruise	Date 1970	Depth (m)	Station 3	2	1	4	5	6	7	8
6	14 April	0	117.6	88.2	26.6		19.0	12.2	12.2	14.9
		5	63.7	56.0	18.2	27.1	19.0	9.5	14.9	
		10		46.2	26.6	27.1	20.3	12.2	10.8	18.2
8	30 April	0	62.2	24.2	42.0	31.6	22.4	15.0	16.4	19.6
		5	35.8	39.2	28.2	47.2	17.0			
		10			32.8		20.8			
10	12 May	0	81.2	63.7	51.1	17.2	23.5	9.1	9.7	7.7
		5	51.8	75.6	51.8	15.4	19.6	8.4	4.2	12.6
		10			60.2	14.0	23.8	23.8	4.2	12.6
11	19 May	0	45.1	36.2	33.7	27.9	24.1	22.2	13.3	11.4
		5	48.3	35.6	17.8	21.6	14.0	25.4	15.3	12.7
		10			34.3	45.8	26.7	16.5	7.6	11.4

APPENDIX 2 (CONTINUED)

CONCENTRATIONS OF PARTICULATE NITROGEN AT EACH STATION IN µG

Cruise	Date 1970	Depth (m)	Station 3	2	1	4	5	6	7	8
12	28 May	0	81.3	31.8	53.6	22.0	24.6	23.0	16.3	11.5
		5	27.1	31.2	32.5	24.4	27.1	24.4	16.2	16.2
		10			42.0	21.7	35.2	21.7	8.1	21.7
Mean for all cruises and all depths			62.8	47.8	36.7	30.6	23.7	18.8	12.3	15.7

APPENDIX 3

PARTICULATE CARBONATE-CARBON CONCENTRATIONS AS DETERMINED IN CRUISES 10 TO 12

Cruise	Date	Concentrations in µg/l at each station							
		3	2	1	4	5	6	7	8
10	12 May	40.5	8.4	79.8	28.8	55.5	21.6	62.7	14.4
11	19 May	8.2	58.4	82.4	154.6	101.0	74.4	61.5	89.6
12	28 May	77.6	27.7	33.0	62.2	17.0	47.6	69.3	68.2
Mean Carbonate-carbon		41.2	31.5	65.1	81.9	57.7	47.9	64.5	57.4
Percent of total particulate carbon in the form of Carbonate-carbon		9.15	14.05	19.96	36.55	31.77	28.92	50.65	41.78

APPENDIX 4

TOTAL ORGANIC CARBON AS DETERMINED ON CRUISE 12, 28 MAY 1970 (CARBON IN mg/l)

Depth (m)	Station 3	2	1	4	5	6	7	8
0	1.494	2.575	1.660	1.245	1.162	1.245	0.996	0.747
5	1.245	1.079	1.245	0.996	1.162	1.245	0.747	0.747
10			1.162	1.577	1.494	0.996	0.913	0.830

APPENDIX 5

RESULTS OF DIURNAL STATION RUN ON 2--3 APRIL 1970

Time	Particulate organic carbon in µg/l				Particulate Nitrogen in µg/l			
	Om	3m	7m	11m	Om	3m	7m	11m
0900	173	142	156	200	28	18	24	20
1100	186	139	133	138	22	22	22	21
1300	206	126		121	30	19	23	19
1500	126	115	140	129	23	19	23	21
1700	142	152	135	222	29	23	21	23
1900	229	215	140	215	44	46	21	24
2100	116	111	129	186	18	18	19	30
2300	144	124	128	256	22	22	18	31
0100	197	171	143	229	32	30	21	28
0300	209	114	148	233	32	21	21	29
0500	207	175	161	154	38	30	27	18
0700	132	169	118	161	48	33	22	24
Mean	172	146	139	187	30	25	22	24
Std. dev.	38	31	13	45	10	8	3	5
% var.	65	71	26	72				

APPENDIX 6

KANEOHE MUNICIPAL SEWAGE TREATMENT PLANT AND KANEOHE MARINE CORPS AIR STATION

SEWAGE TREATMENT PLANT EFFLUENT ANALYSIS RESULTS

Plant	Daily Mean Flow in $m^3 \times 10^6$	Date	Measurement results in g/m^3			
			Organic Carbon			Particulate Nitrogen
			Particulate	Dissolved	Total	
Municipal	9.5	1 May	4.87	8.98	13.85	0.85
		5 June	5.51	4.20	9.71	0.81
		Mean	5.19	6.59	11.78	0.83
Military	4.5	22 May	9.65	11.55	21.20	1.16
		27 May	11.99	10.40	22.39	1.17
		Mean	10.82	10.97	21.79	1.165

APPENDIX 7

TOTAL ORGANIC CARBON CONCENTRATION IN g/m^3 IN STREAM EFFLUENT

FROM STREAMS FEEDING INTO KANEOHE BAY

Date	Kawa	Kaneohe	Kaa-hala	Heeia	Kaha-luu	Unnamed	Kaa-leae	Wai-hole	Unnamed	Wai-kane	Haki-puu
23 May	2.57	2.57	2.41		5.48	3.40	3.33	1.33	4.32	0.75	1.91
27 May	0.75	0.91	0.99	1.24	1.01	1.01	1.41	1.66	1.33	0.99	0.66
Mean	1.66	1.74	1.70	1.24	3.28	2.24	2.37	1.49	2.82	0.87	1.29
Flow $m^3 x10^6$	6.0	43.9	3.8	18.9	61.3	5.3	11.3	15.9	8.3	25.7	8.3

ACKNOWLEDGMENTS

Throughout my study, many people gave freely of their time and knowledge. My indebtedness to them is immeasurable. Some special recognition must go to Dr. Donald Gordon whose willing guidance has been invaluable, and to Dr. John Caperon for the use of his nutrient data, to Dr. S. Allen Cattell for the use of his chlorophyll a data, and to Mr. George Krasnick for the use of his Carbon-14 productivity data. I additionally wish to express my gratitude to Mr. Sidney Nakamura and Mr. Frank Stone, both with the Division of Sewers of the City and County of Honolulu; to Mr. Paul Lee, Department of Sanitation of the Kaneohe Marine Corps Air Station; to Mr. Salwyn Chin of the Water Resources Division of the United States Geological Survey and to all those at the Hawaii Institute of Marine Biology who aided me in my study.

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